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Technical Memorandum 33-550

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M. L. Peelgren

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PREFACE

The work described in this report was performed by the Propulsion Division of the Jet Propulsion Laboratory.

CONTENTS

ABSTRACT

The nuclear reactor powered ion propulsion system described is an advanced completely modularized system which lends itself to development of prototype and/or flight type components without the need for complete system tests until late in the development program. This modularity is achieved in all of the subsystems and components of the electric propulsion system including (1) the thermionic fuel elements, (2) the heat rejection subsystem (head pipes), (3) the power conditioning modules, and (4) the ion thrusters. Both flashlight and external fuel type in-core thermionic reactors are considered as the power source.

The thermionic fuel elements would be useful over a range of reactor power levels. Electrical heated acceptance testing in their flight configuration is possible for the external fuel case. Nuclear heated testing by sampling methods could be used for acceptance testing of flashlight fuel elements. The use of heat pipes for cooling the collectors and as a means of heat transport to the radiator allows early prototype or flight configuration testing of a small module of the heat rejection subsystem as opposed to full scale liquid metal pumps and radiators in a large vacuum chamber. The power conditioner (p/c) is arranged in modules with passive cooling which allows complete prototype testing. The ion engines are typically matched with one or more p/c modules and are the same size for any power level propulsion system of interest.

I. Introduction

Nuclear Electric Propulsion (NEP) systems are attractive for unmanned outer planet missions (Ref. 1). The NEP system is an integration of a thrust subsystem and a power subsystem. The thrust subsystem is comprised of power conditioning modules, ion engines, thrust array translator and thrust vector control. The power subsystem includes the reactor/radiator, neutron shield, control and control drives. The thrust subsystem designs have been modularized in solar electric studies such as Reference 2, as well as in recent nuclear electric systems studies which utilize extensions of the solar electric thrust subsystem technology (Ref. 3, 4 and 5). The power subsystems investigated to date have not been modular. The emphasis here, then, will be on the extension of the modular concept to the power subsystem.

There are basically two in-core thermionic reactor concepts presently being investigated; the flashlight and the external fuel concept. The United States thermionic reactor program is concentrated on the flashlight concept with the external-fuel converter as an advanced concept. The flashlight concept (Ref. 6) has several thermionic converters connected in series within each fuel element similar to flashlight batteries. The nuclear fuel is located inside a cylindrical emitter. The external-fuel concept (Ref. 7 and 8) has one thermionic converter per fuel element and each converter can be connected into any series-parallel electrical matrix desired. The reactor fuel is on the outside of a cylindrical emitter. The flashlight fuel element technology is further developed than the external-fuel technology but additional technology work is required on both concepts.

Collector coolant schemes are illustrated in Fig. 1 which shows the various combinations of either pumped liquid metal and/or heat pipe cooling for the collector and the radiator heat rejection system. Under the heading "Heat Exchanger" in Fig. 1, "NO" means that the reactor pumped coolant tube or heat pipe is a single continuous element from reactor to radiator. "YES" means that there is a physical, metallic barrier (i.e., heat exchanger) which separates the coolant circuit of the reactor from the coolant circuit of the radiator.

A completely modularized thermionic reactor propulsion system conceptual design for both the flashlight and the external fuel in-core reactor concepts is described. The collector coolant scheme envisioned for both cases uses a separate heat pipe for each collector and a separate radiator heat pipe for each flashlight or external-fuel thermionic fuel element. The evaporator end of the radiator heat pipe is mechanically coupled to the condenser end of the reactor heat pipe. This two heat pipe in series heat rejection scheme allows assembly of the shield, bus bars, and radiator components onto a completely assembled thermionic reactor core. The heat pipe to heat pipe mechanical joint is designed to provide a rigid, high thermal conductance bond structure.

The uniqueness of the modular concept design described in this paper is the coupling of the radiator heat pipe to the collector heat pipe of individual TFE's. This heat-pipe to heat-pipe coupling provides a single TFE module with its own heat rejection device. This concept allows for testing of a full scale flight type TFE and heat rejection module during the technology development stage of a thermionic power subsystem. Also, the flight type or the final design external fuel modules may be individually performance and acceptance tested prior to final assembly into a thermionic power system. Flight type modules of the flashlight configuration may be performance tested in-pile but the elements chosen for this type of test could not be used in the flight system. Acceptance tests of the flashlight modules would entail non-destructive methods to indicate potentially defective elements.

The collector cooling and the radiator heat rejection concepts described in this paper require high performance heat pipes with either potassium or sodium as the working fluid. These high performance heat pipes incorporate either an annular or an arterial liquid return passage for minimum liquid friction pressure drop. For the collector temperatures of interest (<115 $^{\circ}$K) good performance has been obtained with sodium heat pipes (Ref. 9 and 10). Sodium annular wick heat pipe experimental data obtained to date indicates that axial heat flux of greater than 7 kW/cm^2 of vapor transport area is attainable (Ref. 9) and a sodium heat pipe lifetime of greater than 16,000 hr has been achieved (Ref. 10).

Satisfactory heat pipe performance has not been attained with potassium as the working fluid. Potassium heat pipe performance appears to be more sensitive to impurities in the heat pipe and is more susceptible than sodium to nucleation and boiling for a given liquid annulus width.

However, it should also be mentioned that problems have been encountered (Ref. 11) in obtaining high performance with annular wick sodium stainless steel heat pipes. The use of niobium-1% Zr as the heat pipe material in place of stainless steel is expected to result in high performance, reliable long-life heat pipes.

II. System Descriptions

The technology development costs for new power subsystems and thrust subsystems are reduced and system reliability is increased by using the completely modular concept. Development testing of small prototype and/or flight type modules may be carried out on a low cost basis before full scale, high cost complete system tests are needed. The inherent redundancy of modular systems can raise the system reliability because it allows continued system operation with failed modules. This modularity concept is incorporated in all major components of this propulsion system. The modular approach is applicable to a wide range of power levels; however, this discussion is focused on a power subsystem with an output of 100 kWe delivered to the thrust subsystem. Two types of in-core thermionic reactors are considered as the power source for this 100 kWe propulsion system.

A. Flashlight Thermionic Reactor Powered Propulsion System

1. Power Subsystem

The power source for this system is a fast spectrum, heat-pipe cooled, thermionic reactor delivering 100 kWe to the thrust subsystem at the end of life. A typical cross section containing 162 Thermionic Fuel Elements (TFE) of the flashlight configuration is shown in Fig. 2. The reactor diameter is approximately 76 cm. Each TFE is electrically isolated from the others in the core. Surrounding the collector sheath of each TFE is a hexagonally shaped heat pipe (Fig. 3). The heat pipe evaporator wick is integrally bonded to the collector sheath. The heat pipe vapor space is that portion of the heat pipe between the wick and the hexagonal shell. The heat pipe working fluid is sodium. This hexagonal heat pipe extends beyond the core and connects to a matching radiator heat pipe as shown in Fig. 4. All electrical leads are brought out from the end of the TFE opposite that of the radiator heat pipe connection. The average electrical power density in the thermionic converter is 3.7 watts/cm^2 with a conversion efficiency in the converter of 12%. Control is by means of 18 control drums in the radial reflector. The reflector material is BeO with B_4C as the neutron poison material. The design allows for a 20% loss in power output from both failed and degraded performance TFE's during the lifetime of the reactor (20,000 full power hours). The excess reactivity available at the beginning of life is 6%.

The radiator consists of 162 heat pipes, one for each TFE, mounted in a cylindrical array approximately 1.1 meter in diameter. Each heat pipe is approximately 2 cm in diameter. The radiator heat pipes are connected to the reactor heat pipes by means of tapered joints (Fig. 5), one for each reactor to radiator heat pipe pair. These joints have accurately ground tapers to insure complete intimate contact between the mating surfaces. A preload on these tapered surfaces is assured by means of the locking nuts which are an integral part of the joint. The temperature difference associated with the contact thermal resistance is partially compensated for since this temperature difference increases the contact pressure thereby reducing the thermal resistance. Since there are no coolant pumps, heat exchangers or volume compensators associated with this heat rejection system, prototype and flight configured heat pipes may be tested individually or in small groups. Therefore full scale testing of the complete system is not believed necessary until late in the development schedule. In addition, the actual flight radiator heat pipes may be individually acceptance tested prior to flight. Meteoroid penetration criterion is used to determine probability of puncture failure.

The remainder of the power subsystem uses conventional components. The 18 control drums, each with its own drive motor and safety override mechanism, are modular in concept and the reactor can continue to operate with 4 failed motors or stuck drums. The LiH neutron shield, the structures for the shield, reactor, radiator, etc., the TFE electrical interconnections and the instrumentation and controls are not modular, but do not contain any single point failure points. The electrical output of the TFE's is parallel connected to buses. In the same manner, the power conditioners are also parallel connected to these buses. Therefore, failures or degraded performance is shared by the remaining modules.

2. Thrust Subsystem

The thrust subsystem is comprised of power conditioning modules, ion engines, thrust array translator and thrust vector control (Fig. 6). The ion engines may have varying beam diameters for various power levels. In the range of interest the accelerating voltage is varied to change the specific impulse. Eighteen 30 cm ion engines were used in this 100 kWe propulsion system study. The ion engines are mounted on a structure which translates in two directions perpendicular to the thrust vector. This arrangement permits adjustment of the thrust vector to pass through the CG of the spacecraft even though some engines have failed and/or to compensate for unequal performance. In addition, there are several engines in the group which are gimbaled for roll control. The Thrust Vector Control (TVC) monitors and controls these operations. Each ion engine is typically matched to its own power conditioner. The power conditioner for each engine consists of one or two power conditioning modules which are attached to radiator panels for passive cooling. This allows testing of completely prototype ion engines and power conditioning modules in a space simulated environment.

The propellant tankage consists of two tanks equally spaced, fore and aft, about the CG of the spacecraft. The propellant is taken from each tank uniformly during thrust phases of the mission. Slight differences in the propellant inventory can be compensated for by the thrust array translator. These tanks of mercury propellant also provide the necessary gamma shielding to protect the spacecraft science and controls. For this reason, some excess propellant is included to insure an acceptable gamma dose rate at the end of the mission.

B. External-Fuel Thermionic Reactor Powered Propulsion System

1. Power Subsystem

As in the above case, the power source for this system is a fast spectrum, heat pipe cooled, thermionic reactor delivering 100 kWe to the thrust subsystem at the end of life (Fig. 7 and 8). However, this core contains 300, 3.49 cm diameter, Thermionic Fuel Elements (TFE's). The reactor diameter is approximately 90 cm. Each group of four TFE's is electrically isolated from the other groups in the core. The four TFE's in a group are parallel connected at their emitters and collector leads (Fig. 9). The collector and emitter buses are considered rigid members in the 4 element clusters. The series connections between clusters are also considered rigid. To allow differential movement of emitters and collectors the electrical leads (pantographs) from the buses to the collectors and emitters are flexible in the axial direction. The buses, in addition to maintaining fuel element spacing in the core, also provide the support for the fuel elements. Each TFE has a fueled emitter assembly with a central cylindrical tube collector. This collector is also the reactor heat pipe. Converter electrical connections are made at both top and bottom of the core. This allows the designer several options in selecting the heat pipe configurations for the reactor and radiator. The first option, as in the case of the flashlight concept, is a full length reactor heat pipe extending from one end of the reactor and connected by a mechanical joint to a full length radiator heat pipe (Fig. 10a). The second option also utilizes full length reactor heat pipes extended from both ends of the reactor connecting to half length radiator heat pipes of twice the diameter (Fig. 10b). This results in lower pressure drops within the radiator heat pipes. The third option utilizes half length reactor heat pipes extending from both ends of the reactor, connecting to half length radiator heat pipes (Fig. 10c). This option gives further multiplicity of heat pipes and reduces the required collector heat pipe performance. The TFE with the emitter external to the collector is amenable to electrical heating acceptance tests to verify operating condition of actual flight TFE's prior to the formation of clusters and installation into the reactor. The external-fuel reactor concept, however, is penalized by the requirement for high temperature thermal insulation between the periphery of the active TFE core and the inside of the reflector. The average TFE electrical power density of this reactor is 4.2 watt/cm^2 and the converter efficiency is 11%. Control and radial reflectors are similar to the flashlight reactor described above. Also allowance is made for 20% loss of reactor output power during the design lifetime of 20,000 full power hours. The excess reactivity at the beginning of life is 6%.

Except for the number of heat pipes, the radiator in this system is similar to that of the flashlight system. They are connected to the reactor heat pipes by the same type joint described above (Fig. 5).

2. Thrust Subsystem

The entire thrust subsystem of this propulsion system is the same as that for the flashlight reactor powered propulsion system described in Section A.2. above.

III. System Optimization

In order to arrive at good design values for system components, it is necessary to understand the influence of variations in component design values, on the system design values. A good example of this is the influence of collector temperature on system design values. As the collector temperature is raised, the size and weight of the radiator, which is conductively coupled to the collector, decreases. However, as the collector temperature is raised the reactor efficiency decreases, requiring possibly more thermionic fuel elements and more reactor thermal power to produce the required electric output; hence an increase in reactor and radiator weight. Thus models are required for all components of the propulsion system. A comprehensive Nuclear Electric Propulsion (NEP) system model has been developed at JPL (Ref. 12) which to date includes the external-fuel reactor. A model for the flashlight reactor will be available shortly; however, for the purposes of this paper the flashlight reactor/radiator combination discussed here fits within the same envelope as the external-fuel reactor/radiator combination.

Of particular interest in the trade-offs described in this paper is the model for the reactor, which is an improved model based on Ref. 8, and the annular heat pipes, which are modeled from Ref. 13. In order to calculate and optimize the system design values, trade-offs were required for the following component design values:

- Emitter diameter
- Emitter length
- Emitter thickness
- Collector thickness
- Collector temperature
- Reactor thermal power density

The radiator diameter is internally optimized, by sizing the radiator heat pipe condenser diameter to use all the available capillary head. It was found that the optimum in these variables was quite broad, and fully insensitive to system power level, allowing some degree of flexibility in the choices involved. Table 1 summarizes the results of influence studies made around the optimum at 100 kWe.

There is a significant system performance penalty for a design with a heat pipe heat exchanger as shown in Table 1. The use of sodium or potassium as the heat-pipe working fluid has only a small effect on system weight based on the results of Table 1. Therefore, sodium should be the first fluid used in the hardware program because the experimental results to date are better with sodium than with potassium.

IV. Conclusions

The modular concept provides: (1) a potential method of reducing complexity and cost of a nuclear thermionic reactor power subsystem technology development program, (2) flight qualified power modules useful in subsystems ranging from 70 kWe to 250 kWe which covers the range of interest for unmanned electric propulsion missions, (3) a method of preflight acceptance testing the actual modules that are used in the flight system, and (4) an overall power subsystem with inherent redundancy and no single point failure mode. These benefits are obtained without increasing propulsion system weight.

In addition to the above, the complete modular system has the following benefits:

1. Excess modules can be included to allow for module failures or degradation.
2. The small but finite possibility of penetrating a well armored radiator tube is no longer an important consideration.
3. Because of heat pipe operating characteristics, reactor startup may be possible without a large auxiliary electric power source since no pumps or line heaters are required. It may also be possible to shut down during coast periods and greatly reduce the system full power hour lifetime requirements.
4. Reactor/radiator connections do not involve liquid metal weld joints or launch site filling operations. (Individual heat pipes are filled, sealed and tested prior to final assembly.)

5. Modularity allows replacement of modules with spare flight modules during final assembly and checkout.

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Table 1

Influence of Parameter Changes in Propulsion System Specific Mass

Parameter	Base Value	Changed Value	$\Delta\alpha/\alpha$, %
Emitter Diameter	1.6 cm	1.4 cm	+2.6
		1.8 cm	+1.0
		2.0 cm	+2.4
Emitter Length	25.4 cm	20 cm	+1.1
		30 cm	+5.3
Emitter Thickness	0.1 cm	0.15 cm	0
		0.20 cm	+4.5
		0.30 cm	+9.3
Collector Thickness	0.26 cm	0.28 cm	+1.1
		0.24 cm	+2.6
Collector Temperature	1150°K	1100°K	+6.3
Reactor Thermal Power Density	32 W/cm^2	35 W/cm^2	+2.4
		30 W/cm^2	+3.1
Heat Pipe Heat Exchanger ΔT	50°K	0°K	-5.6
Heat Pipe Fluid	Na	K	+3.3

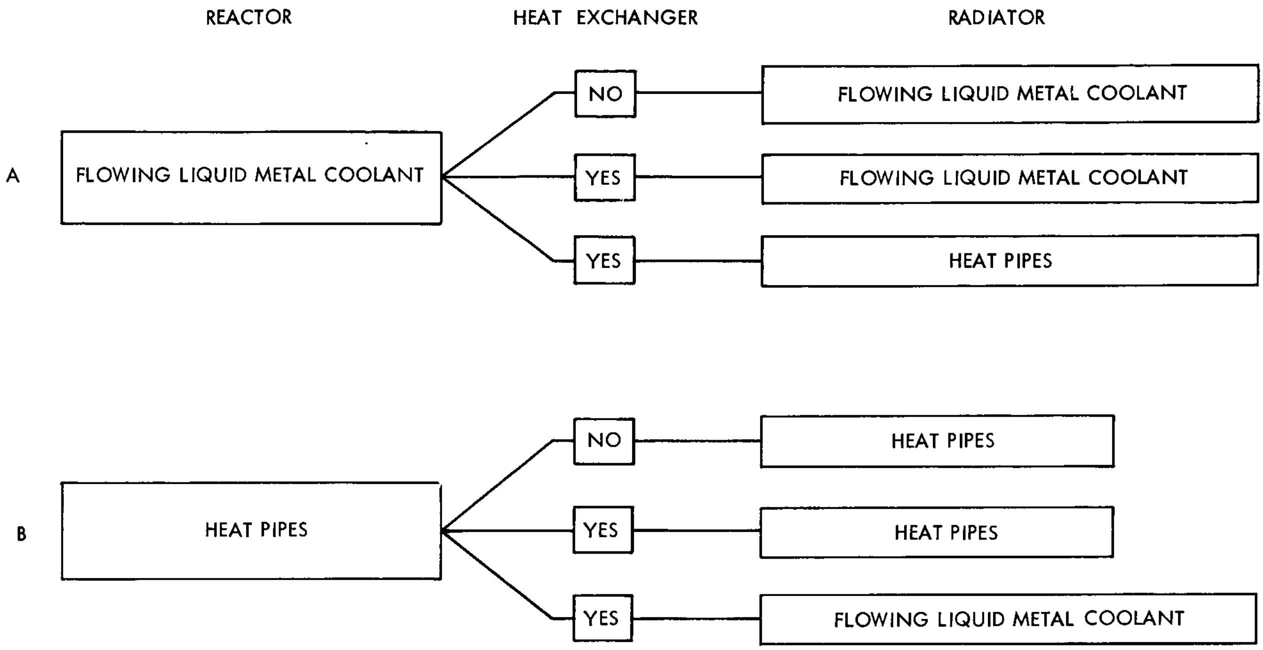

Fig. 1. Reactor cooling schemes

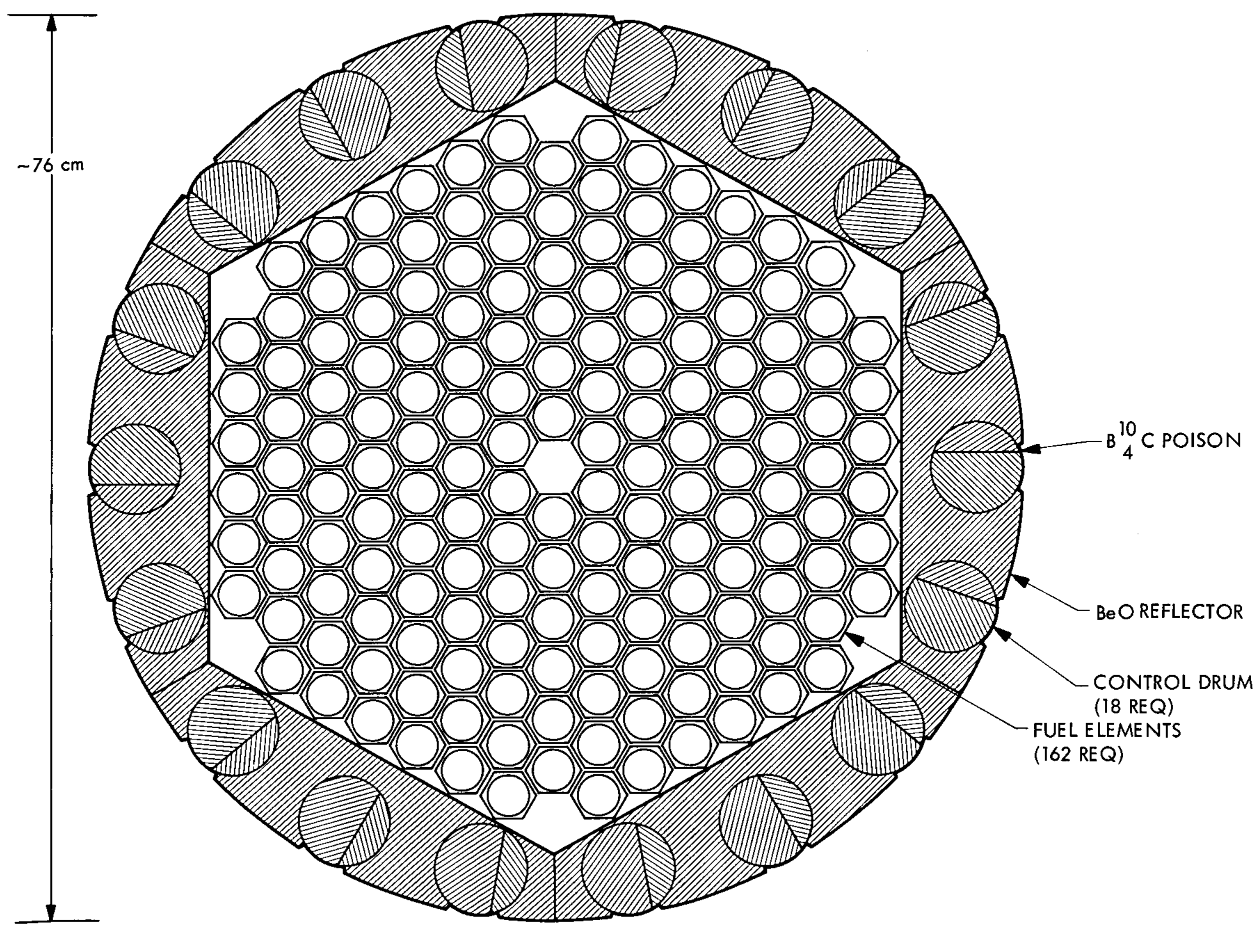

Fig. 2. Flashlight reactor - core cross section

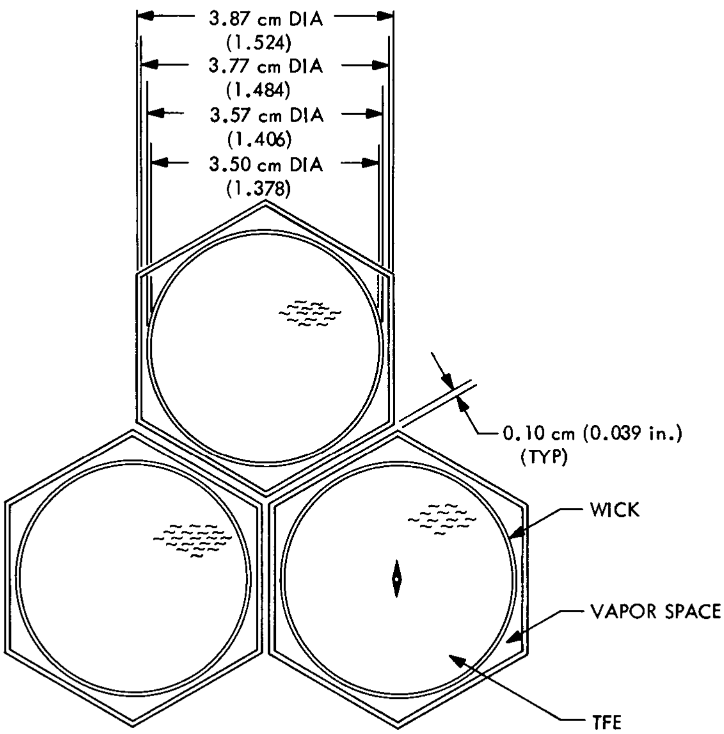

Fig. 3. Hexagonal heat pipes - cross section

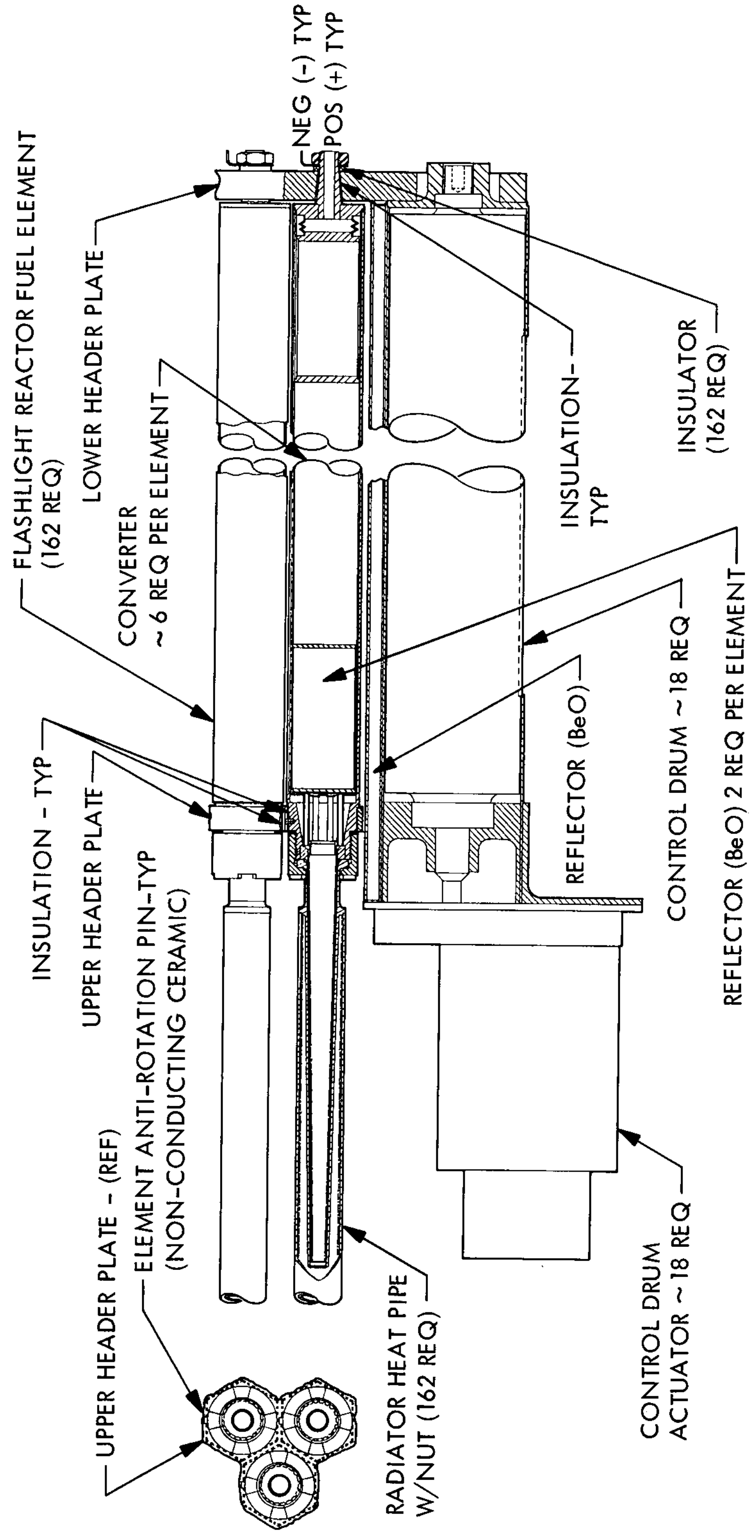

Fig. 4. Flashlight reactor - vertical section

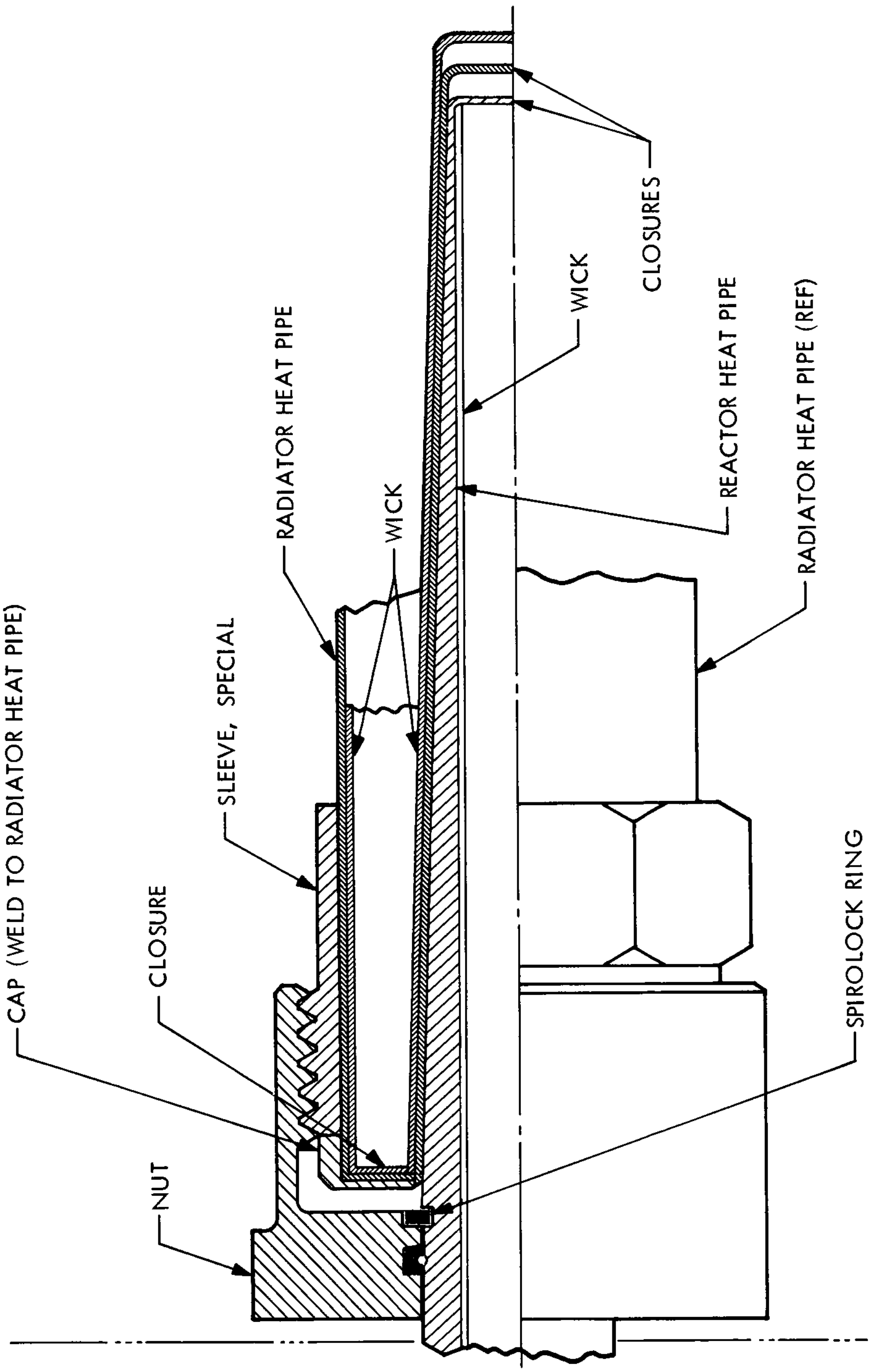

Fig. 5. Heat pipe to heat pipe connector

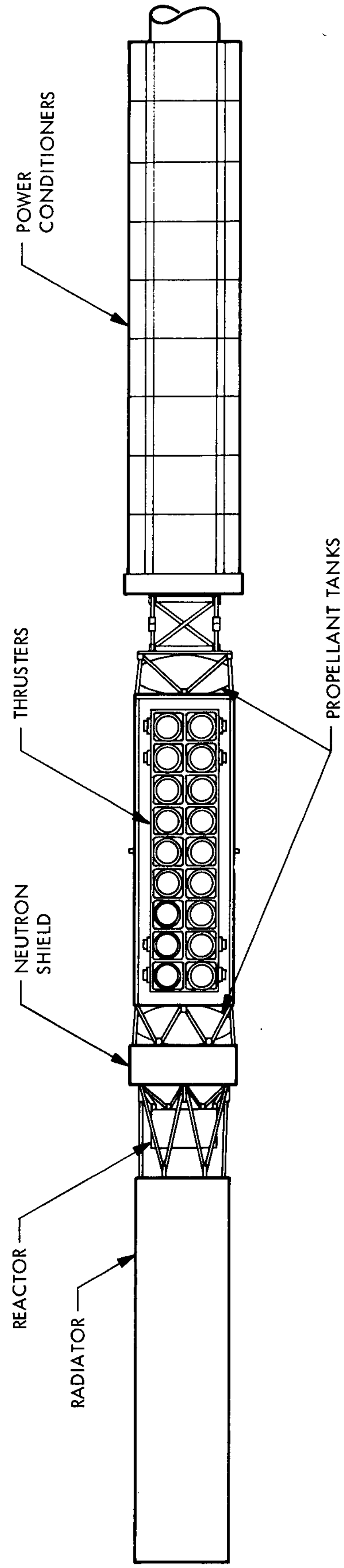

Fig. 6. NEP system flight configuration

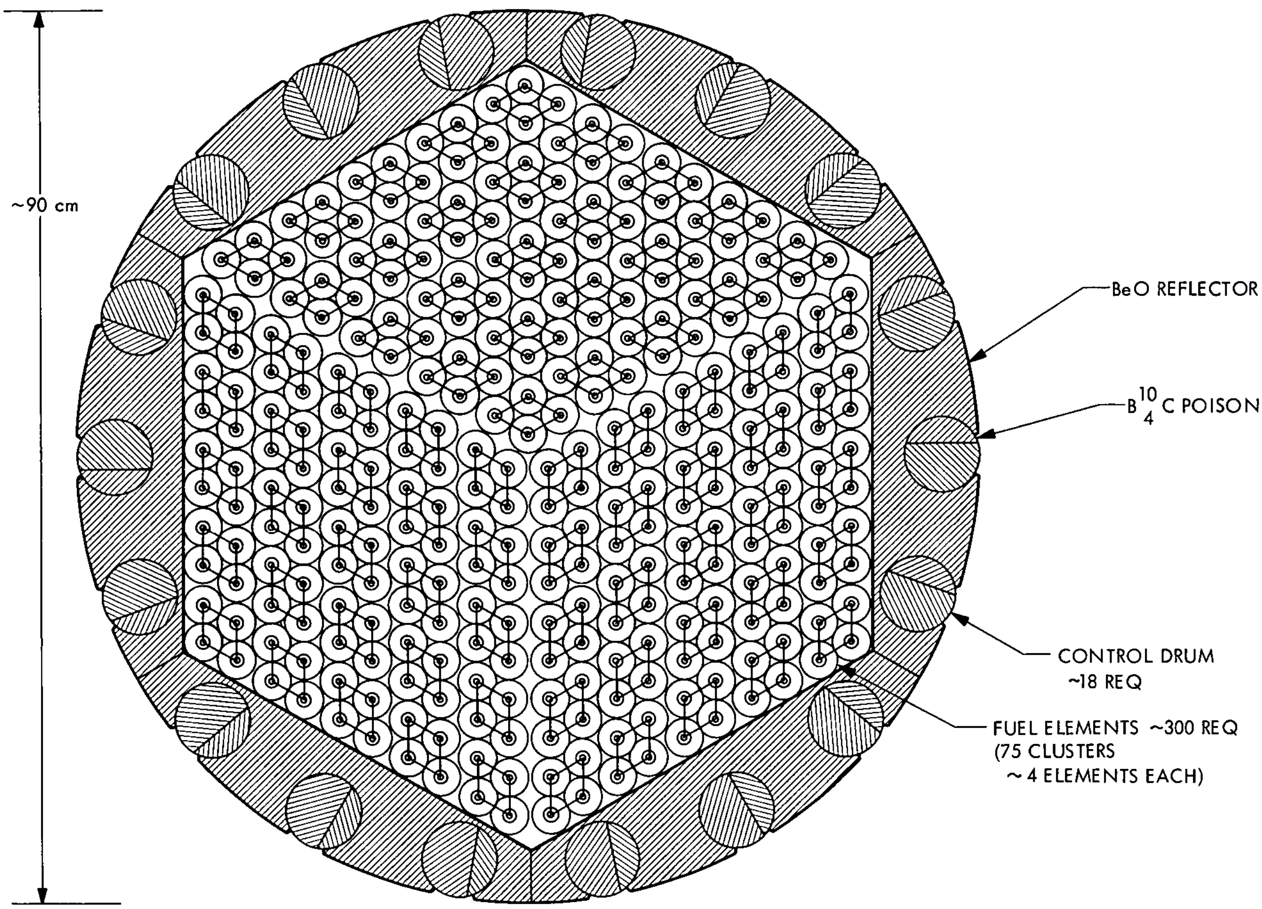

Fig. 7. External fuel reactor - core cross section

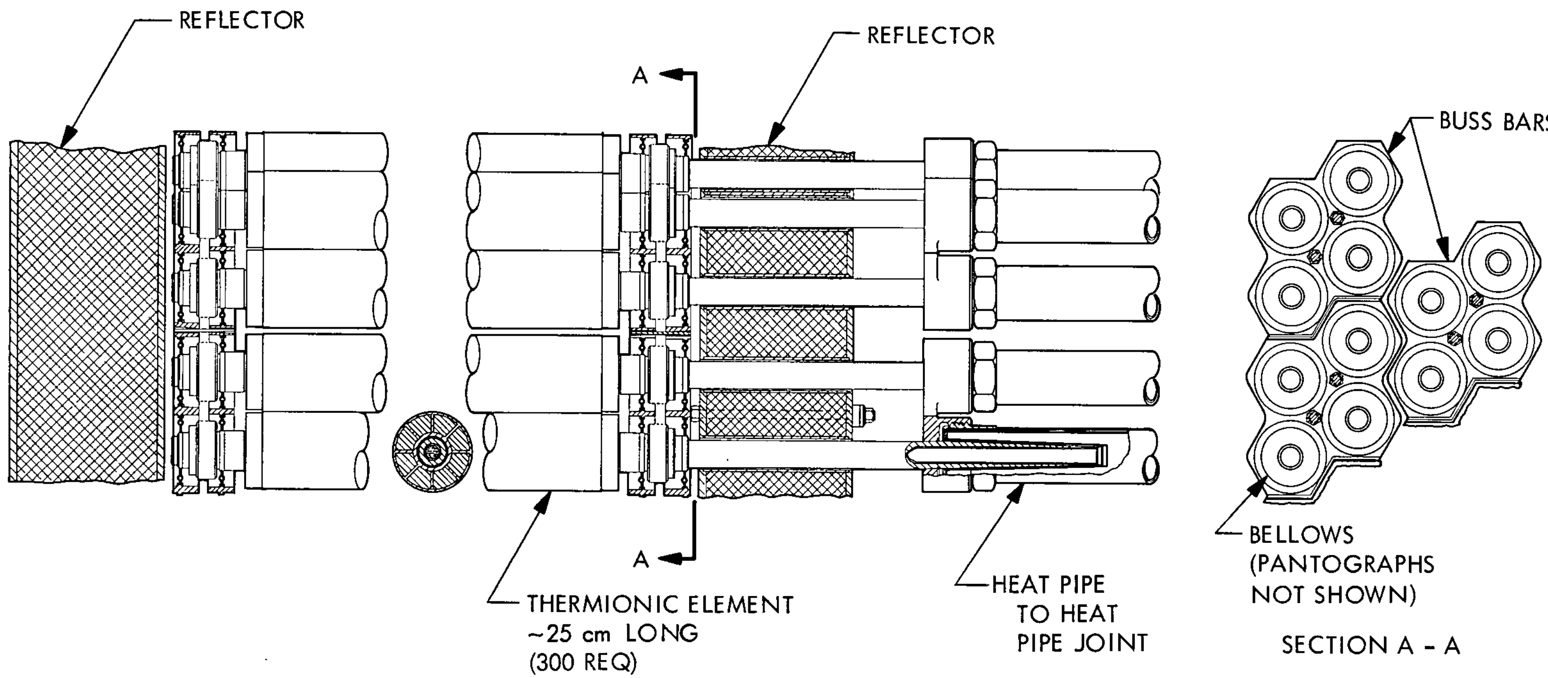

Fig. 8. External fuel reactor - vertical section

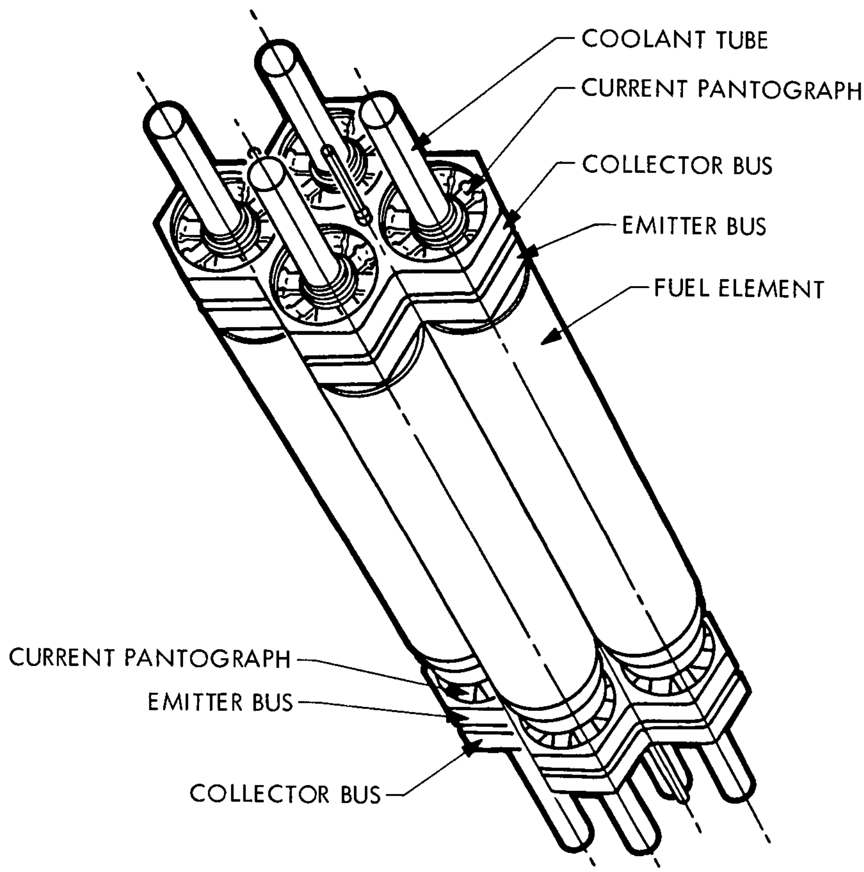

Fig. 9. Four TFE cluster - external fuel reactor

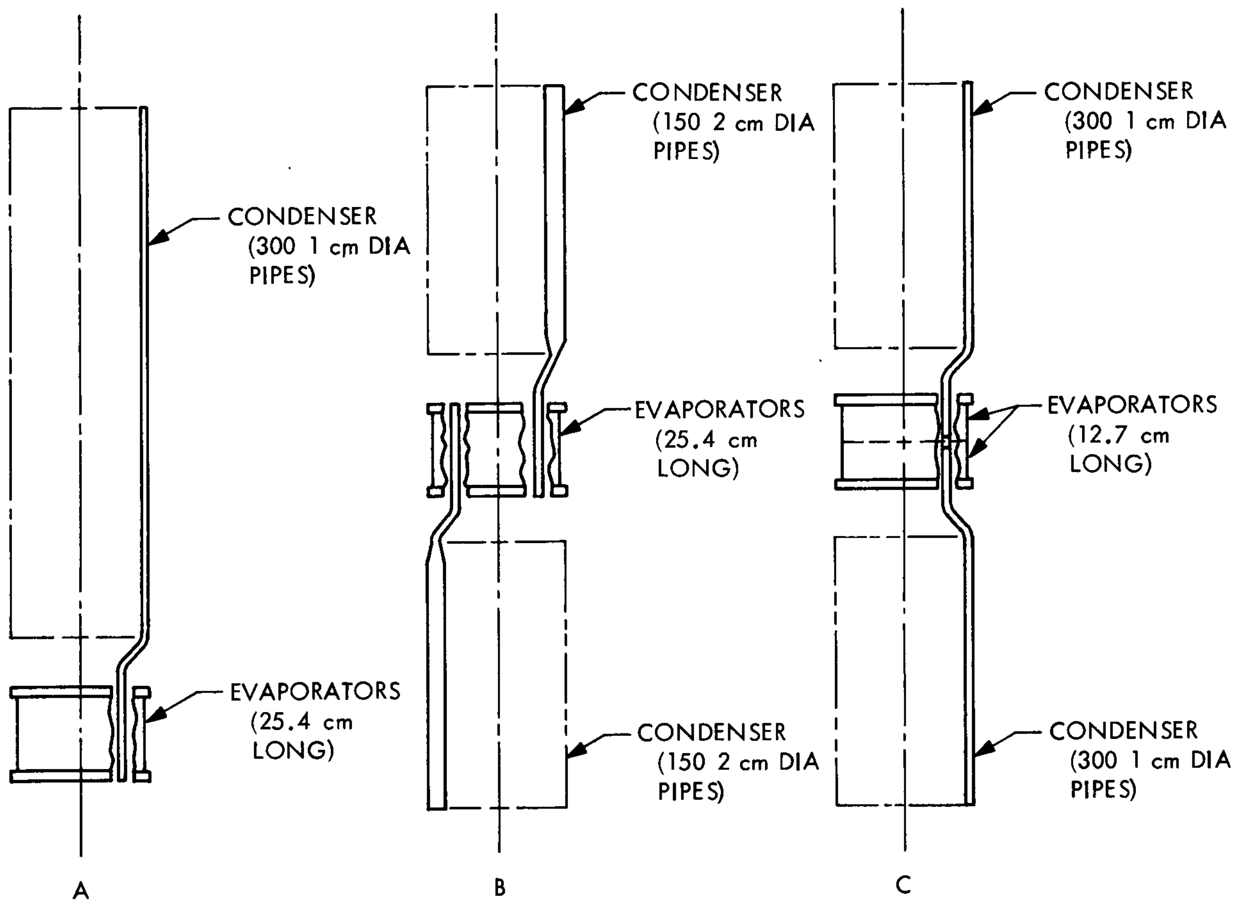

Fig. 10. Reactor/radiator configuration options

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